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PRODUCIBILITY AS A DESIGN FACTOR IN NAVAL SHIPS

by

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ABSTRACT

There are many producibility concepts which affect the characteristics of a naval ship. These concepts must be addressed during the early phases of the ship design process while the ship is still flexible. Since these producibility concepts may affect ship performance and technical risk, as well as ship characteristics and cost, a rigorous tradeoff analysis is required.

This paper provides examples of producibility concepts which should be addressed during the ship design process. An evaluation procedure is presented to assist in the gathering and the organizing of information required for an objective tradeoff analysis. The ship synthesis model "ASSET" is utilized as the principal design tool to determine ship impact and the cost of producibility concepts. One of the primary recommendations of the authors is that the Navy needs to increase the visibility of producibility as a design factor in naval ships by developing rigorous evaluation tools, cataloguing producibility concepts for considerations in future designs, and establish an advocate for ship producibility within the design organization.

INTRODUCTION

Most of the material written on the subject of ship producibility focuses on enhancing efficiency and producibility during the ship building process after the basic ship design has been completed. Ship producibility is in fact not a serious consideration during the early design phases of a ***naval*** ship. Questions arise such as: Why is producibility not a serious factor in the early stages of the design of naval ships? Can ship producibility be enhanced by designing it into a naval ship from the outset? If the answer is "yes" (which the Authors have concluded is true), how can producibility considerations best be incorporated into the naval ship design process7 These are the fundamental issues to be addressed in this paper.

The Authors have approached this subject on a broad conceptual 'level. The basic research was conducted at M.I.T. by Ledr Bosworth as a graduate thesis with Captain Graham serving as his Advisor. The intention was to develop source material on the subject of ship producibility for incorporation into the M I T graduate curriculum. The objective of this effort was to provide a framework for future studies in this area.

This Paper will summarize the more thorough report (Reference 1) and will cover the following topics:

- Unique Features of a Naval Ship
- Producibility as a Design Factor
- Producibility Conceptual Framework
- Wartime Producibility
- Peacetime Producibility Categories

- Conclusions and Recommendations

UNIQUE FEATURES OF A NAVAL SHIP

Naval combatant ships (submarines, aircraft carriers, frigates, destroyers, cruisers) are among the most complex products man designs and produces. There is no other system that must perform so many diverse and highly sophisticated functions simultaneously. The diversification of functions in naval combatants is caused by the requirement to be effective in all four welfare areas (subsurface, air, surface, and strike); be mobile; operate efficiently in an extremely hostile natural environment; survive weapon effects; and sustains itself for long periods of time and over great distances away from a logistic base. To a designer this means that there are numerous major design elements to address throughout the design process.

It has been estimated that a naval combatant ship consists of approximately 100 major components and subsystems. Some of the major components include: radar, sonar, weapon launcher, computer complex, communications complex, propulsion prime mover, electrical generator, machinery control system, and hull structure. Each of these in isolation represents a very sophisticated system often incorporating advanced technology. Most of these components have been developed prior to the integration process of ship design. However, in some of the more ambitious ship design programs, a number of key components are developed concurrently with the development of the ship design.

The size as well as the shape of naval ships must be constrained for practical reasons of mobility and affordability. For this reason the physical integration of combatant ships represents a major challenge to package the widely diverse functions into a compact system design. The temporal integration of naval ships is even more important. All functions of a naval ship are expected to work simultaneously with extremely fast reaction times.

The necessity for physical and temporal integration of such a large number of widely diverse and complex functions represents the ultimate design challenge. Because each of the functions is so highly interactive with the others, the ship design process is an iterative vice serial set of tasks. Early iterations define the broad concept, middle interations focus on the engineering of component and subsystem interfaces and the later iterations on the development of the engineering details required for production. Figure 1 illustrates the iterative nature of ship design by means of a design spiral. The spokes of the wheel represents the design elements which must be integrated into the design. The loops of the spiral suggest a major iteration of the design process leading to a balanced baseline. All engineering design is an iterative process. What makes the design process of naval ships unique is the number of diverse functions and the degree of tightness in integration.

There are other important differences in naval ships as opposed to other complex engineering systems which have relevance to this discussion of engineering design and efficiency in production. Naval ships have relatively high unit cost (in the vicinity of 1 billion dollars) and are rarely produced in numbers greater than 30. Thus there is not the opportunity to exploit the efficiencies of mass production. The Navy can rarely afford to experiment with a prototype. The first production ship becomes an operational unit in the fleet and therefore must be engineered and produced correctly the first time. An additional difference relates to the requirement to maintain these ships at the cutting edge of state-of-the-art engineering for the lifetime of the class (up to 50 years). This demands that naval ships be flexible and have the capacity for future growth.

All of the above observations have relevance to a discussion of ship producibility as a design factor in naval ships. This will be brought out more thoroughly in later sections of this paper.

PRODUCIBILITY AS A DESIGN FACTOR

In recent naval ship acquisition programs, producibility has not been considered a major element in the ship design process for several reasons:

- There exist a myriad of other elements that are considered more critical. There is so much diversification in the functions to be addressed during the ship design process of a combatant ship that the subject of producibility gets buried. In addition, producibility is not critical to the demonstration that the design has the capability to meet the operational requirements for the ship nor -is producibility a factor affecting the technical feasibility of the design. Thus producibility tends to get little attention, especially in the early stages of the design process.

- There has been a decided lack of visibility and external pressure to increase the producibility of the basic ship design. There is no "Advocate" insisting that producibility considerations be incorporated into the design. There is' no threat of cancellation of a ship program if producibility is not an integral part of the engineering development. For many other considerations such as reliability/maintainability, test and evaluation, and integrated logistics support there are strong Advocates. A ship design team can only respond to so many outside pressures.

- There is a perception that the design community does address producibility through weight minimization or cost constraints. Unfortunately producibility ideas are not aggressively pursued for the purpose of reducing production costs. And many producibility concepts tend to increase the size and weight of naval ships and therefore are turned down.

- There is a lack of awareness of the relative leverage in cost reduction and ship impact resulting from ship producibility concepts. Most early stage ship designers are unschooled in modern ship production procedures. There is little data on specific producibility concepts to incorporate into early stage designs.

- There is a lack of a rigorous methodology for the assessment of producibility concepts. The trade-offs among ship effectiveness, cost, and risk are not understood.

Now this is not to say that major ship acquisition programs ignore producibility during the ship design process. In general, the strategy of recent ship acquisition programs is to get the potential shipbuilders involved in the design process at the earliest possible time. However, since the shipbuilders for both lead and follow ships are not usually selected until after the contract design phase is completed, there is a sensitive relationship among the candidate shipbuilders and the Navy that hinders open communications. All the shipbuilders must be treated equally to avoid possible claims for preferential treatment. And, of course, the shipbuilders are all vying for a favored position.' There is also misunderstanding between the Navy's inhouse conceptual ship designers and the shipbuilders' detail designers and planners. Neither have a lot of experience in the others area of expertise.

Although some attempt is being made in addressing ship producibility. in early stage designs, 'the effort is not overly effective. This paper will recommend ways to improve this situation.

PRODUCIBILITY CONCEPTUAL FRAMEWORK

There are two major classifications which are useful for focusing attention on the subject of ship producibility: "wartime producibility" and "peacetime producibility". The former is primarily concerned with schedule and production rate and the latter with acquisition cost considerations. The two classifications will have many producibility concepts in common, but the methods for evaluating those concepts will be quite different.

There has been voluminous amount of material reported on both wartime and peacetine producibility. Understandably greater emphasis has been placed recently on peacetime producibility since that is the condition the Navy and the shipbuilding industry have been in for the past four decades. (Hopefully this will not change.) Except for a brief discussion on wartime producibility in the next section, this paper will focus on peacetime producibility.

WARTIME PRODUCIBILITY

In wartime, or in a pre-war mobilization effort, schedule is of the essence and the task of constructing a large number of ships in time to effect the outcome of the conflict takes overwhelming precedence. Considerable historical data concerning wartime producibility exists and this type of data dominated post World War II producibility research material (See References 2 and 3).

In the thesis by Bosworth, a brief history of wartime producibility has been provided. The Steps the United- States took to produce the incredibly large number of merchant ships, escorts, and major combatant ships in such a brief period of time are reviewed. The Authors will assume interested readers will review this reference and pass on to the observations and recommendations concerning wartime producibility.

The primary lessons from history for wartime producibility are:

- There must be a recognized national need and a measurable goal. Tremendous resources must be mobilized and shortcuts through the bureaucratic morass must be realized. This requires a sense of great urgency.

- Series production must be maximized and design changes minimized or phased in gently. The goal is to maximize the number of operational' ships in a given period of time. The ships must be effective but sufficient numbers take priority especially for the lower mix ships (merchants, amphibious, logistic, escort ships). A good design needs to be finalized and then turned over to industry for long series production.

- The timing must be accurate. Ships must be ordered months or years before they are delivered in large numbers. This permits a build up of materials and preparation of industrial facilities. The changing tide of war makes production forecasts difficult. There cannot be a stop-and-go decision making process if efficient series production is to take place.

- Design simplification and flexibility must be emphasized. Alternative materials and equipment must-be allowed to prevent competition for critical quantities needed by other programs.

Simplicity in design permits production at second echelon facilities leaving more capable shipyards free to concentrate on the more complicated, high capability ships.

The United States Navy cannot predict the form of its next *war*, but America's dependence *on* the seas certainly suggest the possibility of a lengthy maritime conflict. Such a conflict would require a mix of a relatively small number of highly capable ships (nuclear submarines, nuclear aircraft carriers and cruisers, and surface combatant ships (cruisers and destroyers) and a large number of lower capability ships (cargo ships, escorts, logistic and amphibious support ships).

The "high mix" ships are absolutely required for our Navy which emphasizes power projection and sea control. These ships are by necessity large and highly sophisticated. In peacetime, it takes over 10 years to design and construct a lead ship of this type and an additional 10 years to build out the class. The key to the "low mix" ship is numbers. As was experienced during the World *wars*, very large numbers of these less capable ships are required to keep the sea lines of communication open.

The general conclusion of the Authors is for the United States Havy to continue the emphasis on designing and producing high and mid mix warships during peacetime. These ships would be the primary "come as you are" components of our Navy forces at the time of conflict. These ships could not be produced fast enough to have an impact. in other than an extended duration war. In parallel, the Navy should plan 'a -mobilization effort to produce large numbers of less sophisticated low mix ships.

The specific recommendations for a mobilization effort for large numbers of low mix ships include:

- Predesign to the detailed plan level of a number of austere, low mix, wartime designs. These designs would be maintained current ("evolved" as are the sophisticated designs) and would encompass the following features:

  - smaller/simpler for production at alternate shipbuilding sites (not otherwise usable for major naval combatant construction).

  - use of alternate subsystems (not necessarily optimum from. an effectiveness standpoint) such as propulsion plant or armament that do not compete with the limited supplies available for the exisiting pre-war sophisticated designs.

  - simple to operate for manning by hurriedly trained reservists.

  - future growth capability so that the designs could incorporate changing mission requirements. Thus designs would be rather roomy and have generous margins.

  - flexibility of design to accommodate alternate combat systems as -available or as desirable for various wartime missions.

  - lesser standards for habitability, environmental control, and other items to simplify and speed construction.

- Validate the detailed designs by actual construction of a limited number of prototypes. This would also provide an opportunity to train mobilization production personnel and provide affordable ships for use in training, reserve duty, and testing programs.

- Identify potential production bottlenecks to allow development of mobilization production capabilities. For example, if propulsion reduction gears were a primary bottleneck, incentive3 through legislation could be provided for private development of such a capability or machinery to that purpose could be stockpiled.

- Develop an assessment model for wartime ship designs. This design/schedule synthesis model would integrate component lead times, supply, production site capability, and cost-benefit to permit examination of a wide variety of designs in early phases of design.

The two key recommendations relate to the design and production of the austere wartime ships. The detailed design plans need to be in hand prior to the crisis and validated by prototype construction. The list of austere wartime designs to be assembled might include:

* Escort Frigate (ASW)

Escort Frigate (AAW)

* Escort Carrier

- Multi-purpose Cargo (general cargo, roll-on/roll-off, container)

  Oil Tanker

  Landing Craft

* Mine Warfare Craft

  Fast Patrol Boat (missile)

  Diesel Attack Submarine

(The asterisk [*] indicates higher priority)

These designs and the follow-on prototype construction will of course compete with the design and construction of the Navy's mainstream ships. The Authors feel that about 5% of the total budget might be a reasonably level of investment for this effort.

PEACETIME PRODUCIBILITY CATEGORIES

In peacetime, the fundamental thrust in ship producibility **is** reduction in acquisition cost. One can consider five broad categories Of peacetime producibility: Fleet Concept, Preliminary Ship Layout, Production Details, Shipyard as Factory, and Programmatic Strategy. Each of these will be briefly described below.

Fleet Concept

Producibility should--be an issue when considering the most cost effective composition of the fleet. The Authors have already described the concept that the Navy should concentrate on building the large, complex warships during peacetime in order to have them ready at the start of a conflict. Smaller, less complex ships can be built in large numbers in a shorter period of time during the build-up period prior to a conflict.

Other fleet concepts include Admiral Zumwalt's high mix and low mix policy of mixing more sophisticated ships with less sophisticated ones in order to attain sufficient numbers. The lower mix ships would be severely constrained ships and would be relatively easy to build in large numbers. Another fleet concept **issue** centers on the trade-off between multi-mission and single mission ships. The single mission ships would be smaller, less complex and easier to produce. Other proposals for commercial standards on some naval ships, and the idea of having a changeable payload are other examples of Fleet Concepts. The concept of commercial standards would permit more efficient ship production, especially in shipyards primarily experienced in commercial shipbuilding. The idea -of the universal platform which could be outfitted with a wide variation of combat **suites** **is** another Fleet Concept. This concept has recently been thoroughly studied by the Navy.

All of the above fleet concepts effect the performance characteristics and therefore the military effectiveness of naval ships. These-decisions must therefore be made by the customer, the Naval Operator, in conjunction with those skilled at estimating the ship impact and cost implications of the tradeoffs. These decisions must be made before the start of a serious ship acquisition project.

Preliminary Ship Layout

Once a ship design team has been provided with performance requirement3 and design constraints, it proceeds to develop the design following the iterative phases of the Navy's ship design process (feasibility studies, preliminary design, contract design and detailed design). Producibility options which impact general arrangements, subdivision, dimensions, shape, or subsystem selection belong in this Preliminary Ship Layout category. These option3 must be investigated while the ship design characteristics are still fluid (i.e. before the design is frozen). Therefore they must be addressed during feasibility studies and preliminary designs.

The dilemma is that during the early design phases, the size of the design team is limited while the requirement for conducting numerous fundamental coat vs. performance tradeoffs leading to a selection of subsystems and ship characteristics is overwhelmingly demanding. Thus the resources available to pursue producibility tradeoff options are limited. This is unfortunate as the leverage for affecting the cost of the design through incorporation of producibility ideas may be greatest during these early design phases. With recent advances in computer aided ship design, a wider variety of options can be investigated with fewer manpower assets.

Some example3 of producibility concepts which should be addressed early in the design process when ship characteristics are still fluid include the use of various material3 for structure, outfit and distributed systems (piping, cable, etc.); various schemes to simplify the installation of distributed systems; the variation of margins and design standards; and the increase in ship size and roominess to permit easier installation of equipment and outfit of the ship. Reference 1 provides a more comprehensive listing of concepts which could effect the ship layout.

The area of Preliminary Ship Layout is the most fertile area for producibility research for the naval ship designer. It is an area where he has substantial control (unlike Fleet Concept). It also occurs early enough in the design cycle to have impressive leverage to effect the ultimate design. For these reasons, the Authors concentrated their efforts to develop a producibility assessment methodology suitable for the early ship design phases.

Production Details

Once the general configuration and layout of the ship has been determined (usually fixed during late preliminary design and in some cases by early contract design), the design is refined and additional details developed. If a proposed producibility concept does not impact general arrangements, gross dimensions, shape, subdivision, or subsystem selection, but does impact component selection, material selection, internal compartment arrangements, the item belongs in the Production Details category of peacetime producibility. The tolerance guideline is that the change that follows from incorporation of the design option must be absorbable within the fixed ship configuration and within the design and construction‘ margins. The primary participating parties are the NAVSEA design team that typically produces the contract design, and the ship builder /design agent who refines the contract design into the detail design.

Some example3 of producibility items that fall within the Production Details category include structural details, such as minimizing penetrations in bulkheads and minimizing lightening holes; standardization of structural panels; and simplifying piping runs and fabrication techniques. Certain material tradeoffs, such as the use of glass-reinforced-plastic (GRP) outfitting materials to minimize labor, or the substitution of High Strength Low Alloy (HSLA) Steel for High Yield Strength (HY-80) Steel also belong in Production Details. HSLA has very similar properties to HY-80, but is far easier to fabricate. Palletization might also fall within this category as a means of easing hookups and causing more shop vice shipboard manhours.

Shipyard As A Factory

If the proposed producibility item is not directly ship design dependent, but rather is a function of the physical plant of the production facility, the item belongs in the Shipyard as a Factory category of peacetime producibility. The primary participating party is the shipbuilder. Some examples of the Shipyard As A Factory category include zone outfitting, in which the ship is outfitted by region rather than by system; modular construction, where worker access and productivity is improved by use of hull modules which are later joined together; the development of test standards that support zone outfitting; computer-aided logistic3 and material `control; computer-aided working drawings; and production flow optimization. Many of the techniques of the modern production line fit into this category, such as computer-aided manufacturing (CAM); process lanes or group technology, in which similar facets of different products are catalogued for the purpose of grouping together the manufacture of the different parts; and statistical process control, which is a near real-time measure of the effectiveness of the various Shipyard As A Factory techniques.

The Authors group these concepts in this category because the shipyard must commit to these concepts independent of a specific ship program. Of course once committed, the detail design of a specific ship will be affected, thus these concepts are closely linked with the Production Details category. In fact, consideration of these concepts must be made during the Preliminary Ship Layout phase as ship tightness and arrangements could also be affected.

Programmatic Strategy

If the producibility item is a business or acquisition strategy decision, having less to do with hardware and more to do with scheduling, methods of supply, and contracts, it belongs in the Programmatic Strategy category of peacetime producibility. It wi11 have little impact on the ship design and in some cases minor impact on the production facilities. These programmatic considerations can start with the first conceptual study and will not end until the 1ast ship is produced. The principal participating parties are the navy program office and the shipbuilders. Some examples of Programmatic Strategy include whether material or equipment should be government furnished or shipbuilder provided; whether components should be single or multi-sourced; and the type of contract (fixed price, cost, incentive). The learning curve for ship production is an important factor. Therefore, the decision as to how large a particular ship class should be is vital. Mobilization considerations as to the location of production facilities, the availability of labor, and the workload distribution are additional examples of the Programmatic Strategy category of peacetime producibility.

Relationship Among Categories

All five of the above categories of peacetime producibility are closely related. The reasons why the Authors differentiated these categories is to focus attention on when and' by whom commitment decisions must be made. Figure 2 superimposes the phases of the ship design and construction process and the categories of ship producibility.

The fleet concept issues should be addressed prior to the start of a serious acquisition program. Producibility concepts which could effect ship layout must be decided upon before ship characteristics are frozen. Production details which can be absorbed into the fundamental design need not be addressed until contract and detail design. Programmatic issues and concept3 which impact the production facilities are closely related and must be part of an overall strategy.

PRODUCIBILITY ASSESSMENT METHODOLOGY

As previously explained, one of the reason3 why producibility is not more of a consideration during the early phases of the naval ship design process is due to the lack of a rigorous assessment methodology. The members of the design team are not familiar with the producibility issues nor with the trade-offs. One of the primary objectives of Bosworth's thesis was to develop such a methodology. This paper will summarize this assessment methodology and provide a case study to illustrate its use.

The Authors' assessment methodology consists of six steps as follows:

Step 1. - Characterize Concept. Certain information and data must be gathered and summarized in order to assess a specific producibility concept. Table 1 contains a convenient form for this task. The breadth and level of detail of this data must be consistent with the input required for the next four steps.

Step 2 - Ship Impact. A ship impact analysis is performed to determine the affect of the producibility concept on the ship's gross characteristics. This is generally performed using a ship synthesis model and for minor impact3 marginal cost factors. Bosworth [Reference l] discusses the advantages and disadvantages of five ship synthesis models currently being used to conduct ship impact analysis. A general treatment of the use of ship synthesis models can be found in Reference 4. ASSET Advanced Surface Ship Evaluation Tool, is capable of handling most of the known probability concepts and was determined by the Authors to be the most suitable for ship impact analysis. For producibility concepts with minor impact on weight, internal volume, and manning, marginal factors can be used to determine the overall ship impact. This concept is discussed in References 5 and 6.

Table 2 provides a convenient form for summarizing the results of the ship impact analysis.

Step 3- Cost Impact. Since cost reduction is the primary motivation for considering producibility innovations during peacetime, a thorough cost analysis is required. Although all components of life cycle cost should be investigated, acquisition cost is the most visible cost category in this case. Most ship acquisition cost models consist of estimating the cost of each of the functional areas of the ship (categorized consistent with the Ship Work Breakdown Structure [SUBS]) using cost estimating relationships (CERs) for material and labor as a function of weight. These CERs are based on return costs of recent naval ships. Unfortunately these models are not sensitive to some the proposed producibility concepts since they are inconsistent with the shipbuilding approaches of completed ship acquisition programs. Some recommendations for improving cost estimating for Naval ships are provided in References 7 and 8. In these cases it will be necessary to include as part of the characterization of the concept, an analysis to determine the change to accepted cost estimating relationships. Table.3 provides a spreadsheet type of form to determine the cost impact of producibility concepts.

step 4 - Effectiveness Analysis. The incorporation of a producibility concept into a baseline ship design could alter a performance characteristic such as spread, range, survivability, combat system effectiveness, and operability. However, the usual approach in conducting these types of assessments is to normalize performance features between the baseline and variant designs while conducting the ship impact analysis (Step 2). This is the cleanest way in as much as there will be no change in ship effectiveness and the net impact of the producibility concept will be on ship size and cost. Where it is inconvenient to normalize performance features, the differences should be noted. The Authors have not found any convenient effectiveness assessment models to utilize in these cases. This is a further motivation for normalizing performance.

Step, 5 - Risk Assessment. Any new concept incorporated into a ship design represents an increase in technical, schedule and cost risk. The degree of risk is for the most part evaluated qualitatively and categorized as low, medium, or high. A recent thesis by Walsh [Reference 9] provides a more rigorous approach to evaluating risk in naval ship designs and could be applied to the risk caused by new producibility concepts.

Step 6 - Net Assessment. An overall evaluation of the merits and shortcomings of a producibility concept will consist of all the considerations discussed in Steps 1 Though 5. The Authors have found no comprehensive methodology for combining 211 of the diverse considerations towards a single bottom line type of figure of merit. Table 4 provides a convenient form for summarizing the various considerations in a graphic format.

Since further details are provided concerning the assessment methodology in Bosworth's thesis, the Authors will move on to a brief discussion of a Case Study in order to further illustrate the procedure.

PRODUCIBILITY CASE STUDY

One example is provided to illustrate the viability of the producibility assessment methodology. The producibility concept chosen involves the issue of adding volume to a ship in order to increase the efficiency of installing equipment versus tightening up a ship to decrease ship size and thus materials. This has been a hotly debated issue in recent naval ship designs such as the just completed destroyer design, Arleigh Burke (DDG 51).

The specific volume reducing concept investigated was the deck height reduction approach involving reversing deck framing and reducing the clear deck height criteria. In this study, the baseline design contained the reduced deck height due to the reverse framing and reduced criteria and the variant contained the more volumetrically demanding conventional framing and expanded clear deck height. Thus this producibility assessment is between a volume reduction concept primarily for the purpose of ship weight reduction versus a more conventional shipbuilding approach which would appear to be more producible.

The steps in the producibility assessment methodology discussed previously were followed. The results are summarized here with the more complete study available in Reference 1.

Step 1 - Characterize Concept. Using the Characterization Form suggested, the information to characterize the deck height producibility concept was gathered and summarized (see Table 5). The concept is described, a sketch provided (a picture is worth a thousand words) and the approach to conduct the ship impact assessment using ASSET is presented. The later step is important in the understanding and interpretation of the ship impact results as the Naval Architect must use judgement in modifying the baseline design. What is missing in this characterization is information on the affect on labor efficiency in installing equipment and distributed systems. This will be amplified in the discussion of Step 3.

Step 2 - Ship Impact Assessment. Before a ship impact assessment can be conducted, a baseline ship design must be in hand. In an acquisition project, the most current ship baseline serves as the basis for comparison. For this case study, a baseline needed to be synthesized. The baseline design was based on one developed as a ship design project at MIT and is similar to a baseline described by Goddard in his thesis [Reference 10].

For this ASW frigate, the payload contained a large conformal sonar array and a. towed array, vertical launch ASROC, Harpoon, Seasparrow, and three large Lamps III helicopters. The hull form was a Hull 23 variant, and the material for both hull and superstructure is high tensile steel (HTS). The baseline frigate has two gas turbine prime movers driving twin fixed pitch propellers through an electric, water cooled, AC/AC transmission.

The ship impact assessment was carried out using the ASSET model and the results summarized in Table 6. The more volumetrically demanding deck height concept caused a 3 percent increase in total enclosed volume and increased displacement by about 2 percent. The major weight increases were in the area of structures and distributed systems. Almost 60 percent of the weight increase was in the shell and supports (SWBS 110) and deckhouse (SWBS 750).

Step 3- Cost Impact. As is almost always the case in ship design, cost data and cost analysis is difficult to develop. A set of CER's from ASSET and other cost models were utilized. In this case study, no real analysis was conducted to validate the modifications to certain of the CERs to reflect this producibility concept of increasing the 'ship's volume.* The CERs for labor (indicated as CERh in the form as opposed to CERm for material costs) which should be impacted by tightness are in the fundamental areas of SWBS 110, 120, 130, 150 (structure), 320 (electrical power distribution), 500 (auxiliary) and 600 (outfit). In this case study a slight reduction in the structural CER for labor was utilized but no change in labor cost per ton in the area of distributed systems and outfit. The end result (see Table 7) was a net increase in acquisition cost of 2 percent for the variant. This is simply because the increase in weight caused by the increase in volume of the ship was greater than the reduction. in labor rate that. might be expected when workers have more room to install equipment.

The Authors had no access to any shipyard data to indicate how efficiency could be enhanced by enlarging the ship volumetrically. As is the case in a real life acquisition project, the Cost Estimators are likely to retain conventional CERs unless there is overwhelming evidence to convince them that the CERs can be decreased. For this reason any producibility concept which tends to increase ship weight ends up increasing a cost estimate. This is why analysis of changes in CERs must be a part of every producibility characterization effort.

The issue of ship tightness is fundamental to many of the producibility concepts of the Ship Layout Category. The size and characteristics of the design are affected; therefore, the issue must be evaluated and assessed before the ship design is frozen. Figure 3 displays what intuitively one expects. As tightness is increased, ship displacement is decreased. Ship acquisition cost will decrease proportional to weight until the ship becomes so tight as to cause difficulty installing equipment, distributed systems and outfitting. As the tightness is further increased, the acquisition cost can actually increase.

This particular case study was chosen to illustrate what is often the situation. Producibility considerations are not included in an early stage design because of a lack of cost data to back up what intuitively one knows is right. No one really has a feel for the shape of the cost versus tightness curve of Figure 3. This is an area for fruitful investigation.

<u>Steps 4 and 5</u> - Effectiveness and Risk. In this case- study performance was kept constant between the baseline and variant as

part of the ship impact assessment. Thus there is no appreciable difference in ship effectiveness.

In the area of risk there is also no appreciable difference, Any concept which tightens up the design tends to increase risk slightly. As is usually the case the degree of risk is in the eye of the beholder.

Step 6. - Net Assessment. The overall evaluation of this particular producibility concept of increasing deck heights is summarized in Table 8. The baseline concept of a slightly smaller deck height and therefore smaller ship is better in the categories of ship weight, volume and acquisition cost. The more voluminous baseline has advantages in operability (easier for crew to operate and maintain a looser ship) and risk. All other categories are basically equal.

If this were a real acquisition program where cost is constrained, the decision would be no doubt to stick with the baseline concept. In this case the lower acquisition cost of the baseline might not be true due to the lack of realistic cost estimates. The cost. impact of producibility concepts must' be researched thoroughly as part of the categorization effort.

SUMMARY AND RECOMMENDATIONS

A number of conclusions and recommendations should be noted from this study:

-Producibility is currently not a significant consideration in naval ship design.

- In order to be ready for a mobilization effort, it is recommended that several simple, highly producible mobilization designs be produced through the detailed design level. Furthermore the more promising of these designs should be selected and prototypes constructed to validate the design. These low mix ships could serve in the reserve fleet, be used for training and for testing.

- To increase the awareness of producibility as an important design element for the Navy's ongoing ship design and acquisition programs, a rigorous assessment methodology needs to be developed. Such a methodology consisting of six steps has been proposed. A Ship Producibility Handbook should be prepared describing this assessment methodology and made available to ship design teams. An important part of this handbook would be a file of characterizations of known producibility concepts. The most important part of these characterizations is a fundamental cost analysis of each concept indicating how cost estimating relationships used in cost models should be modified to reflect the concept.

- A Producibility Advocate will be required to ensure that producibility is a significant consideration in naval ship design and acquisition. No such position exists today. Without such a strong visible Advocate little will be accomplished in this area.

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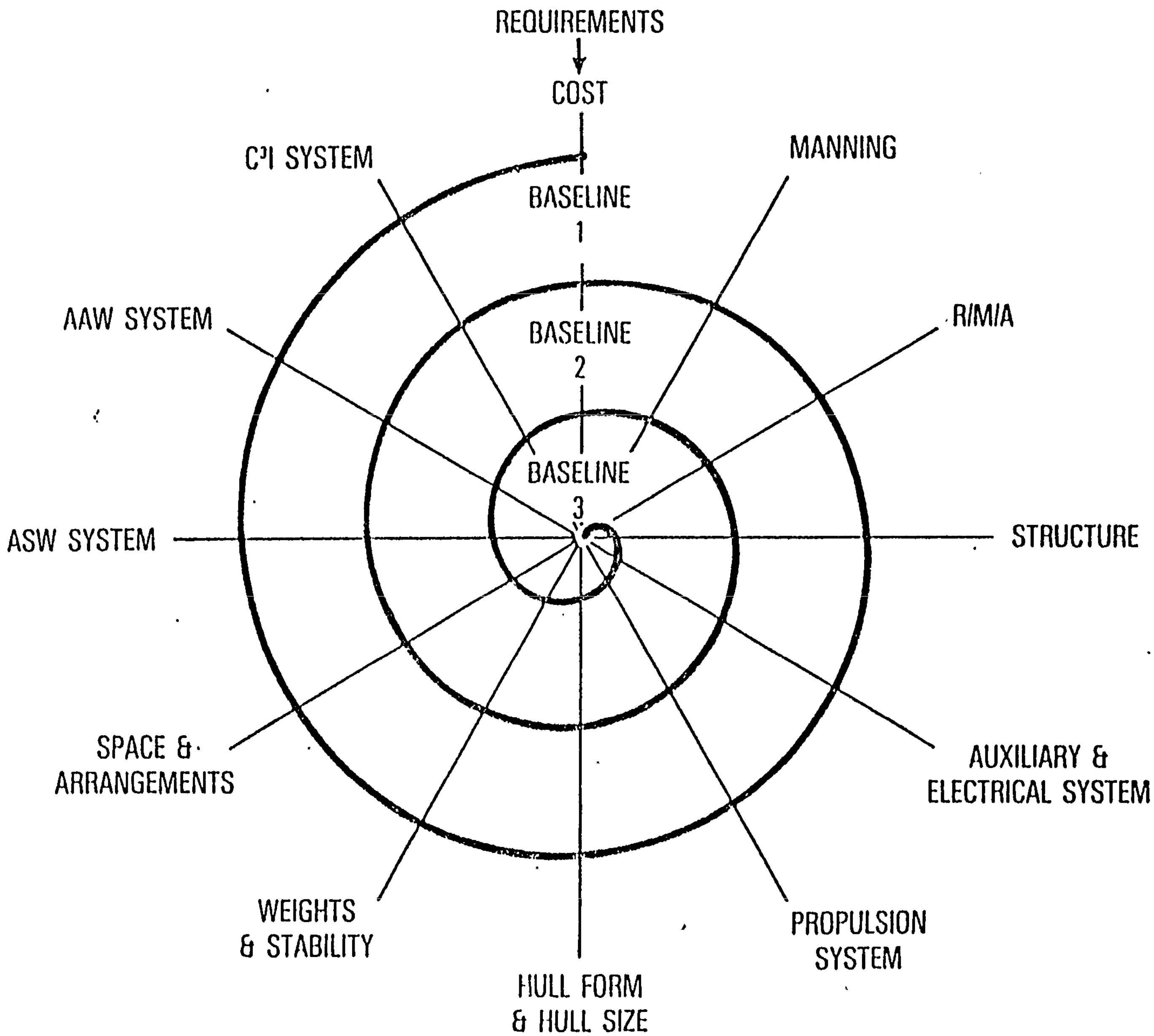
FIGURE 1

ITERATIVE DESIGN PROCESS



PEACETIME PRODUCIBILITY CATEGORIES

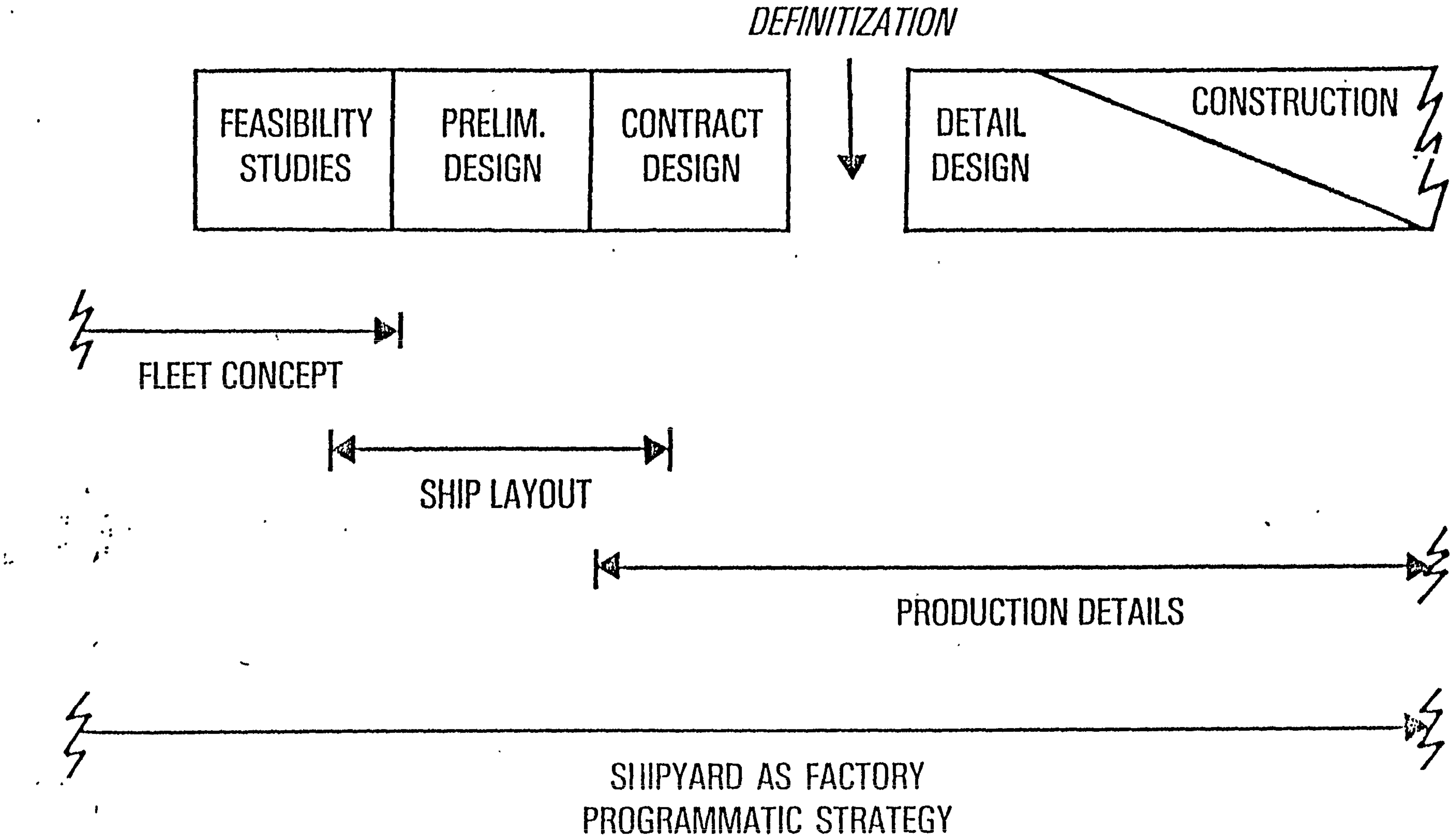


FIGURE 3

SHIP LAYOUT EXAMPLE - TIGHTNESS

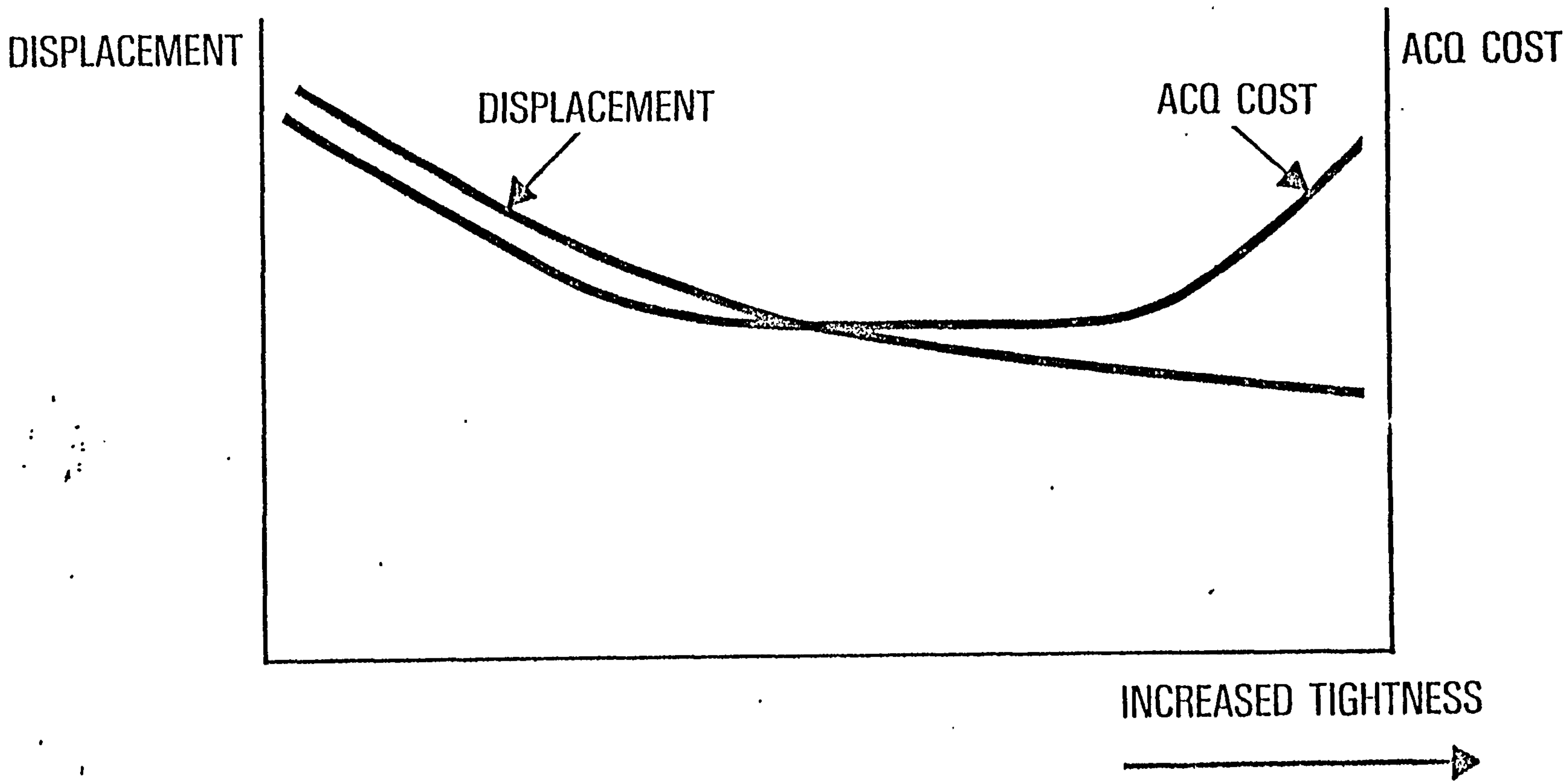


TABLE 1

PRODUCIBILITY CHARACTERIZATION

Producibility Concept Definition Ship: __________ Item: __

Concept: ____ Ref: ___

Description and direct (first order) changes. Include weight, volume, cost, geometry, power, manning.

Tradeoffs between baseline and concept variant. Where will the concept gain and lose?

baseline	variant

Translation to Assessment Tool

Record of ASSET Changes . . . item	baseline	variant
(1)		
(2)		
(3)		
(4)		
(5)		
(6)		
(7)		
(8)		
(9)		
(10)		

Rebalancing Comments: ____

TABLE 2

PRODUCIBILITY SHIP IMPACT

Ship Characteristics Impact   Ship:________   Item: __

Concept:____

parameter	abbrev(dim)	baseline	variant	delta	percent
Length at waterline	LWL (feet)				
Length between perpendiculars	LBP (feet)				
Beam at waterline	B (feet)				
Depth amidships	D (feet)				
Draft	T (feet)				
Displacement, full load	Δfl (LT)				
Volume of hull	∇h (k ft^3)				
Volume of deckhouse	∇dh(k ft^3)				
Total Volume	∇t (k ft^3)				
Stability measue	GM/B (-)				
Total electical load	KW tot (KW)				
Main contin. power available	IP (hp)				
Manning	M (men)				
Maximum sustained speed	Vs (kts)				
Endurance speed	Ve (kts)				
Range	R (nm)				
Payload	W payld(LT)				
Margins	________				
	________				
SWBS Group					
100 Hull Structure	W1 (LT)				
200 Propulsion Plant	W2 (LT)				
300 Electrical Plant	W3 (LT)				
400 Command and Surveillence	W4 (LT)				
500 Auxiliary Systems	W5 (LT)				
600 Outfit and Furnishings	W6 (LT)				
700 Armament	W7 (LT)				
Weight of D+B margin	Wm (LT)				
	==========	======	======		
LIGHTSHIP WEIGHT	W ltshp(LT)				
Fuel & Lubricant weight	Wf (LT)				
Ordnance Load weight	Wa (LT)				
Other Load weight	Wo (LT)				
	==========	======	======		
FULL LOAD WEIGHT	W fl (LT)				

Weight of primary 2-digit SWBS . . .

name	subgroup
______________	______
______________	______

note:small apparent summation errors are due to display roundoff.

TABLE 3

PRODUCIBILITY COST IMPACT

Ship Cost Impact (FY85 $) Ship: _________ Item:__

Concept: ____

SWBS No.	Description	Baseline Weight	Baseline CERm	Baseline CERh	Variant Weight	Variant CERm	Variant CERh	Baseline Cost,k$	Variant Cost,k$	k$ delta	percent
11/12/13	HullMatl A										
11/12/13	HullMatl B										
15	DkhsMatl A										
15	DkhsMatl B										
162	Stacks										
171	Masts										
1X	Rest,Grp 1										
23 (hp)	Propul Units										
241	Reduc Gear										
243	Shafting										
244	Bearings										
245	Propellers										
25	Support Sys										
26	Sup Sys-FO,LO										
2X	Rest,Grp 2										
31 (hp)	ElecPowerGen										
32	Power Distrib										
3X	Rest,Grp 3										
4	Command										
5	Auxiliary										
6	Outfit & furn										
7	Armament										
	D&B Margin										
	LIGHT SHIP		na	na		na	na				
8	Engineering	ditto			ditto						
9	Assembly	ditto			ditto						
ACQ.CONSTRUCTION COST		na	na	na	na	na	na				

Weights for alternate costing SWBS No.

SWBS No.	Description	Baseline	Variant
23	Propul Units		
31	ElecPowerGen		

SWBS No.	Description	Baseline	Variant	%
11/12/13	Hull Matl$			
15	Dkhs Matl$			

	Baseline	Variant
ACQ.CONSTRUCTION COST plus profit %:		
ACQ.CONSTRUCTION PRICE		
plus change orders		
plus NAVSEA support		
plus post delivery		
plus outfitting		
plus H/M/E + growth		
plus payload cost		
UNIT SAILAWAY ACQ COST (k$)		
OPER+SUPPORT SYSTEM COST ($M)		
AVG LIFE CYCLE COST/ship ($M)		

notes: acquisition costs are for follow ship.O+S and LCC are for 30 ships w/ 30 year life.

TABLE 4

PRODUCIBILITY NET ASSESSMENT

Summary   Ship:__________   Item:__

Concept:____

Impact	Comments	baseline better <-------			equal		-------> variant better
Weight	____________________ ____________________	¦	¦	¦	¦	¦	¦
Volume	____________________ ____________________	¦	¦	¦	¦	¦	¦
Stability	____________________ ____________________	¦	¦	¦	¦	¦	¦
Elec Power	____________________ ____________________	¦	¦	¦	¦	¦	¦
Manning	____________________ ____________________	¦	¦	¦	¦	¦	¦
Combat System Effectiveness	____________________ ____________________	¦	¦	¦	¦	¦	¦
Mobility	____________________ ____________________	¦	¦	¦	¦	¦	¦
Survivability	____________________ ____________________	¦	¦	¦	¦	¦	¦
Operability	____________________ ____________________	¦	¦	¦	¦	¦	¦
Acquisition Cost	____________________ ____________________	¦	¦	¦	¦	¦	¦
Operating and Support Costs	____________________ ____________________	¦	¦	¦	¦	¦	¦
Life Cycle Costs	____________________ ____________________	¦	¦	¦	¦	¦	¦
Risk	____________________ ____________________	¦	¦	¦	¦	¦	¦
Other:____________	____________________	¦	¦	¦	¦	¦	¦

Bottom Line:____
____

TABLE 5

PRODUCIBILITY CHARACTERIZATION

Producibility Concept Definition **Ship: BGASWFF** **Item:-1**

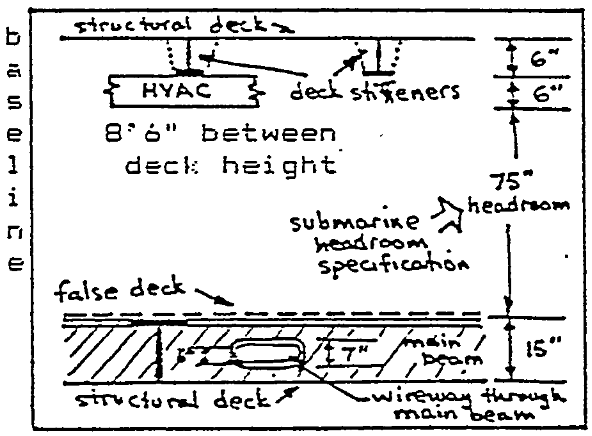
Concept: Deckheight reduction w/ reverse framing Ref:116

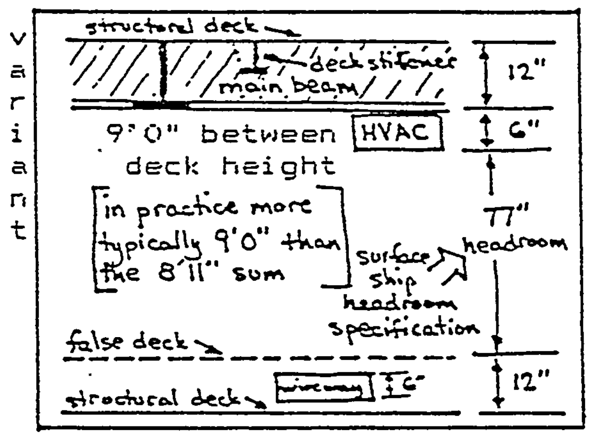
Description and direct (first order) changes. Include weight,volume,cost,georetry,power,ianning.

By using submarine headroom standards (75") and reverse framing (transverse stiffener5 and longitudinal stiffeners on opposite sides of the structural deck they stiffen) deck-height in critical fa1se decked electronic5 spaces can be reduced from 9'0" to 8'6". System envelope5 (wireways, HVGC) remain constant at 6" deep each, weight stays the same, the material cost is constant, labor cost5 of the reduced deck-height version is 5% higher(cutouts in main beam for stif-feners in variant approx equal to cutout for wireway for the baseline. No manning or power changes.

Tradeoffs betnoen baseline and concept variant. Where will the concept gain and lose?

The reduced deckheight will reduce overall ship volume, and the smaller ship should cost less. However, the slightly in-creased labor cost5 of the 9' variant will offset this some. Headroom suffers only in elex spaces(77"->75").





Translation to Assessment Tool

Record of ASSET Changes . . . item

Item	baseline	variant
(1) Hull Deck Location Array	29.5,21,12.5,4	29,20,11,2 *
(2) Deckhouse Height Array	8.5,17,8.5,8.5	9,18,9,9
(3) Deckhouse Average Deck Ht	8.5	9.0
(4) Hull Matl A CER for manhrs	4.6	4.52 **
(5) Deckhs Matl A CER for manhrs	7.4	7.22 ***
(6)		
(7)		
(8)		
(9)		
(10)		

Rebalancing Comments: *After intial balance,adjust up for increased hull size. ** Deck 56% of Hull Mat1 A. ***Deck 50% of tota1 deckhouse. (sample: .36 x.05 = 018; l/l.018 = 982 CERmt = 4.6 x .982 = CERmv = 4.52) baseline=RUBBER.BL.BAL

TABLE 6

PRODUCIBILITY SHIP INPACT

Ship Characteristics Impact   Ship: BGASWFF   Item: 1

Concept: Deckheight Reduction w/ reverse framing; baseline=8'6", variant=9'0"

parameter	abbrev(dim)	baseline	variant	delta	percent
Length at waterline	LWL (feet)	427	430	2.80	.66
Length between perpendiculars	LBP (feet)	427	430	2.80	.66
Beam at waterline	B (feet)	50	51	.33	.66
Depth amidships	D (feet)	38	38	.25	.65
Draft	T (feet)	18.83	18.96	.13	.69
Displacement, full load	Δ fl (LT)	5558	5669	110.20	1.98
Volume of hull	∇h (k ft^3)	558	569	11.06	1.98
Volume of deckhouse	∇ dh(k ft^3)	108	116	7.92	7.30
Total Volume	∇t (k ft^3)	667	686	18.98	2.85
Stability measue	GM/B (-)	.1027	.0989	.00	-3.70
Total electical load	KW tot (KW)	4105	4133	28.10	.68
Main contin. power available	IP (hp)	52209	52514	305.00	.58
Manning	M (men)	301	301	.00	.00
Maximum sustained speed	Vs (kts)	27.95	27.95	.00	.00
Endurance speed	Ve (kts)	20.00	20.00	.00	.00
Range	R (nm)	4500	4500	.00	.00
Payload	W payld(LT)	970	970	.00	.00
Margins				.00	

SWBS Group					
100 Hull Structure	W1 (LT)	1305	1370	65.30	5.00
200 Propulsion Plant	W2 (LT)	429	434	4.70	1.10
300 Electrical Plant	W3 (LT)	252	256	4.10	1.63
400 Command and Surveillence	W4 (LT)	650	651	1.20	.18
500 Auxiliary Systems	W5 (LT)	640	650	10.80	1.69
600 Outfit and Furnishings	W6 (LT)	397	403	6.50	1.64
700 Armament	W7 (LT)	130	130	.00	.00
Weight of D+B margin	Wm (LT)	475	487	11.60	2.44
LIGHTSHIP WEIGHT	W ltshp(LT)	4278	4382	104.20	2.44
Fuel & Lubricant weight	Wf (LT)	1010	1016	5.90	.58
Ordnance Load weight	Wa (LT)	144	144	.10	.07
Other Load weight	Wo (LT)	127	127	.00	.00
FULL LOAD WEIGHT	W fl (LT)	5558	5668	110.20	1.98

Weight of primary 2-digit SWBS . . .

name	subgroup				
Shell and supports	110	389	443	54.20	13.93
Deckhouse structure	150	158	173	15.10	9.56

note:small apparent summation errors are due to display roundoff.

TABLE 7

PRODUCIBILITY COST IMPACT

Ship Cost Inpact (FY85 $) Ship: BGASYFF Item: 1

Concept: Deckheight reduction M/ reverse framing; baseline=8'6', variant-9'0'

SWBS No.	Description	Baseline Weight	Baseline CERm	Baseline CERh	Variant Weight	Variant CERm	Variant CERh	Baseline Cost,k$	Variant Cost,k$	k$ delta	percent
11/12/13	HullMatl A	875.9	3.6	4.6	920.9	3.6	4.52	7182	7478	295.328	4.11
11/12/13	HullMatl B	0	0	0	0	0	0	0	0	0	.00
15	DkhsMatl A	158.3	5.5	7.4	173.1	5.5	7.22	2042	2202	159.762	7.82
15	DkhsMatl B	0	0	0	0	0	0	0	0	0	.00
162	Stacks	31	5.5	7.4	32.8	5.5	7.4	400	423	23.22	5.81
171	Masts	10.7	5.5	7.4	11.3	5.5	7.4	138	146	7.74	5.61
1X	Rest,Grp 1	228.8	2.9	4.3	231.9	2.9	4.3	1647	1670	22.32	1.35
23 (hp)	Propul Units	52209	.41	.15	52512	.41	.15	29237	29407	169.68	.58
241	Reduc Gear	0	6	4	0	6	4	0	0	0	.00
243	Shafting	78.7	31	4	79.7	31	4	2755	2790	35	1.27
244	Bearings	14.6	32	4.5	14.8	32	4.5	533	540	7.3	1.37
245	Propellers	31.8	2	4	31.9	2	4	191	191	.6	.31
25	Support Sys	65.2	50	10	67.2	50	10	3912	4032	120	3.07
26	Sup Sys-FO,LO	24.7	35	9	24.8	35	9	1087	1091	4.4	.40
2X	Rest,Grp 2	10.7	30	5	10.7	30	5	375	375	0	.00
31 (hp)	ElecPowerGen	4105	.86	.63	4133	.86	.63	6116	6158	41.72	.68
32	Power Distrib	92.8	20	40	95.3	20	40	5568	5718	150	2.69
3X	Rest,Grp 3	63.2	20	40	64.2	20	40	3792	3852	60	1.58
4	Command	650.2	15.6	23	651.4	15.6	23	25098	25144	46.32	.18
5	Auxiliary	639.6	28.5	19.3	650.4	28.5	19.3	30573	31089	516.24	1.69
6	Outfit & furn	396.9	12.3	24.2	403.4	12.3	24.2	14487	14724	237.25	1.64
7	Armament	130	3.6	7	130	3.6	7	1378	1378	0	.00
	D&B Margin	475.3	35.9	0	486.9	35.9	0	17063	17480	416.44	2.44
	LIGHT SHIP	4277.7	na	na	4381.9	na	na	153573	155887	2313.32	1.51
8	Engineering	ditto	0	6.62	ditto	0	6.62	28318	29008		
9	Assembly	ditto	0	9.02	ditto	0	9.02	38585	39525		
ACQ.CONSTRUCTION COST		na	na	na	na	na	na	220477	224420	3943	1.79

Weights for alternate costing SWBS No.

SWBS No.	Description	Baseline	Variant
23	Propul Units	203.3	204.6
31	ElecPowerGen	96	96.6

SWBS No.	Description	Baseline	Variant	%
11/12/13	Hull Matl$	3153.24	3315.24	5.14
15	Dkhs Matl$	870.65	952.05	9.35

	Baseline	Variant	delta	percent
ACQ.CONSTRUCTION COST	220477	224420	3943	1.79
plus profit %: 8	17638	17954	315	
ACQ.CONSTRUCTION PRICE	238115	242373	4258	1.79
plus change orders	19049	19390	341	
plus NAVSEA support	5953	6059	106	
plus post delivery	11906	12119	213	
plus outfitting	9525	9695	170	
plus H/M/E + growth	23811	24237	426	
plus payload cost	276200	276200	0	
UNIT SAILAWAY ACQ COST (k$)	584559	590073	5515	.94
OPER+SUPPORT SYSTEM COST ($M)	31221	31289	68	.22
AVG LIFE CYCLE COST/ship ($M)	1706	1711	5	.29

notes: acquisition costs are for follow ship. O+S and LCC are for 30 ships w/ 30 year life.

TABLE 8

PRODUCIBILITY NET ASSESSMENT

Summary **Ship: EGASWFF--** Item:1

Concept: Deckheight reduction w/ reverse framing

Impact	Comments	baseline better		equal		variant better
Weight	variant weighs more		X			
Volume	variant:vol deficient	X				
Stability				X		
Elec Power				X		
Manning				X		
Combat System Effectiveness				X		
Mobility				X		
Survivability				X		
Operability	lower overhd in BL could limit rigging access				X	
Acquisition Cost	due reduced size of the baseline		X			
Operating and Support Costs	baseline better.but not statis. significant			X		
Life Cycle Costs	BL better.but not statistically signif.			X		
Risk	both are low risk. variant is standard practice			X		
Other:	BL concept: some question re: transition from false deck to non-false-deck. However, difference in height is only 3" more than the variant.			X		

Bottom Line: The baseline, with 8'6" deckht, is almost 2% better in acq cost w/ no significant penalties.

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